Tomographic measurement of the phase-space distribution of a space-charge-dominated beam

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Brookhaven National Laboratory
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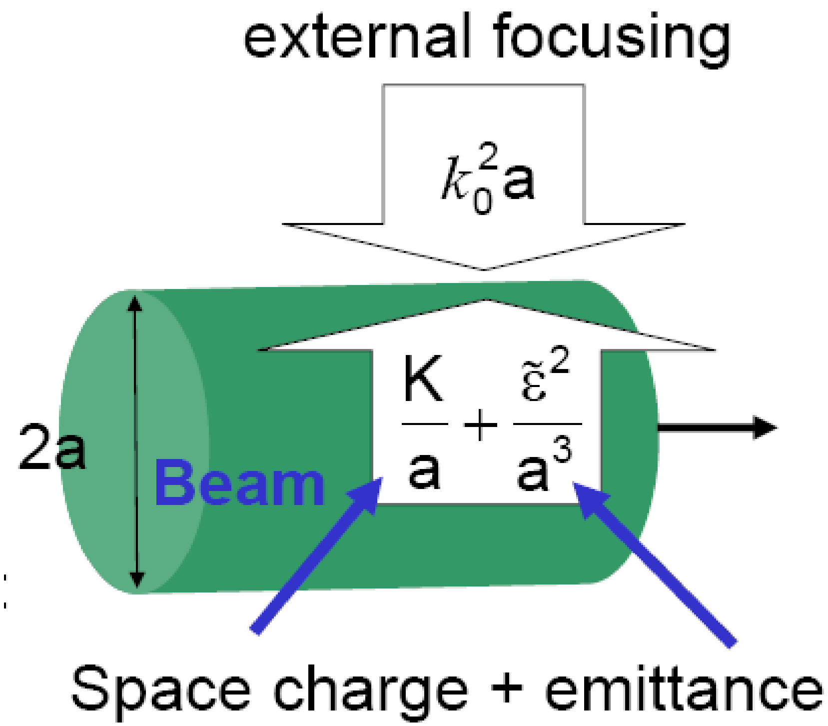
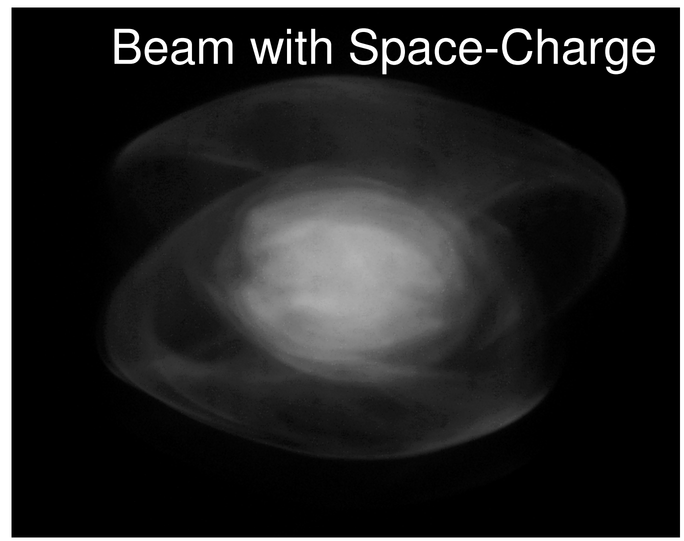
Beams with Space-Charge

Space Charge Force

$$F_{SPACE-CHARGE} = F_{ELECTRIC} + F_{MAGNETIC}$$

$$F_{MAGNETIC} = -\frac{v^2}{c^2} F_{ELECTRIC}$$

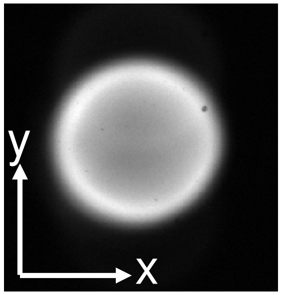


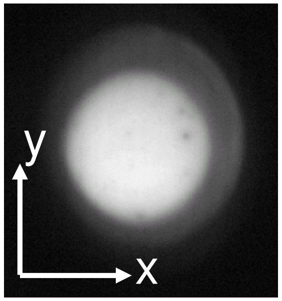


Distributions can be very complex!

Motivation

- Beams near the source:
  - Are high in space-charge
  - Have distributions that are in not in equilibrium
  - Can be born with halo particles





Approach

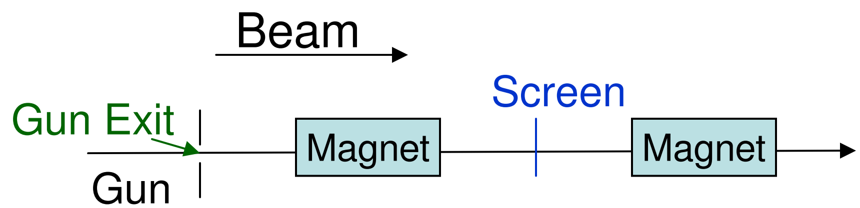
- We need to develop an accurate phase space diagnostic
- Tomography is a good candidate, but to date, has been used only for beams with little space charge
- <u>This study</u> demonstrates the use of tomography for beams with intense space charge

Outline

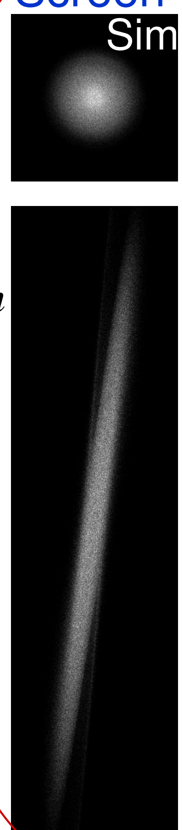
1. Example
2. History/Overview
3. Beams with Space Charge
4. Simulation/ Validation of Tomography
5. Experimental Results
6. Conclusion

Motivation Example

- Initial Conditions?
- Input in Simulations?



Screen



Gun Exit:

$\varepsilon_x = \varepsilon_y = 33.0\mu m$

$X = Y = 2.0mm$

$X^{'} = -10.0mrad$

$Y^{'} = -10.0mrad$

Screen

Gun Exit:

$\varepsilon_x = \varepsilon_y = 13.0\mu m$

$X = Y = 2.0mm$

$X^{'} = -10.0mrad$

$Y^{'} = -10.0mrad$

Screen

Gun Exit:

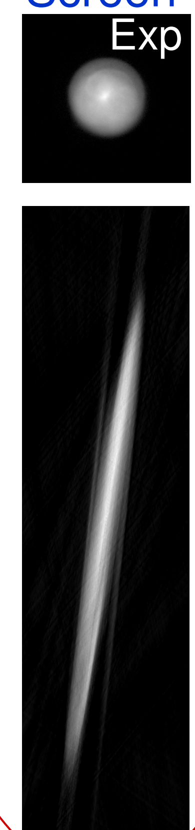
$\varepsilon_x = \varepsilon_y = 33.0\mu m$

$X = Y = 2.0mm$

$X^{'} = -25mrad$

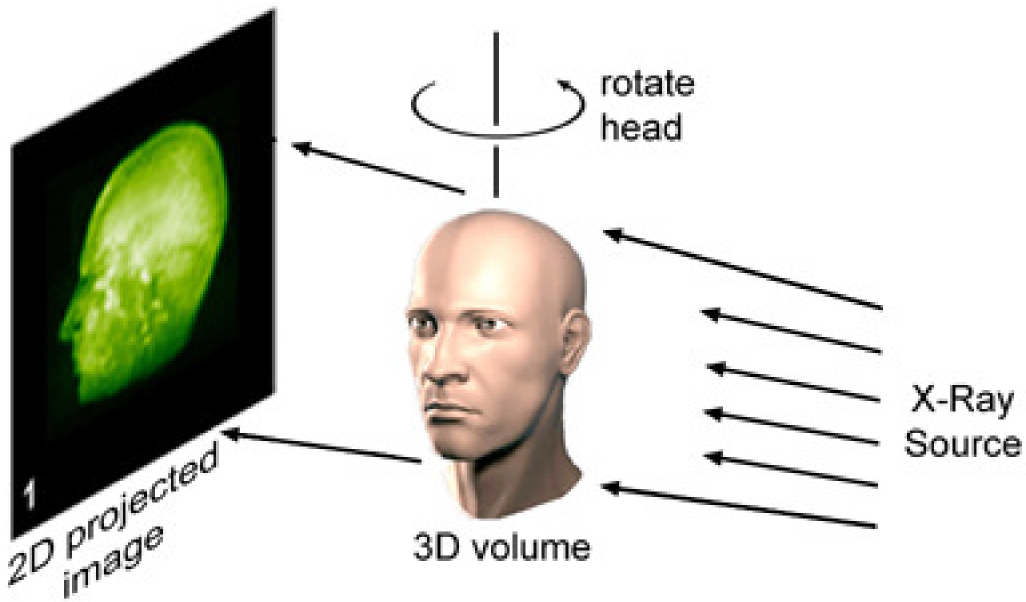
$Y^{'} = -25mrad$

Screen



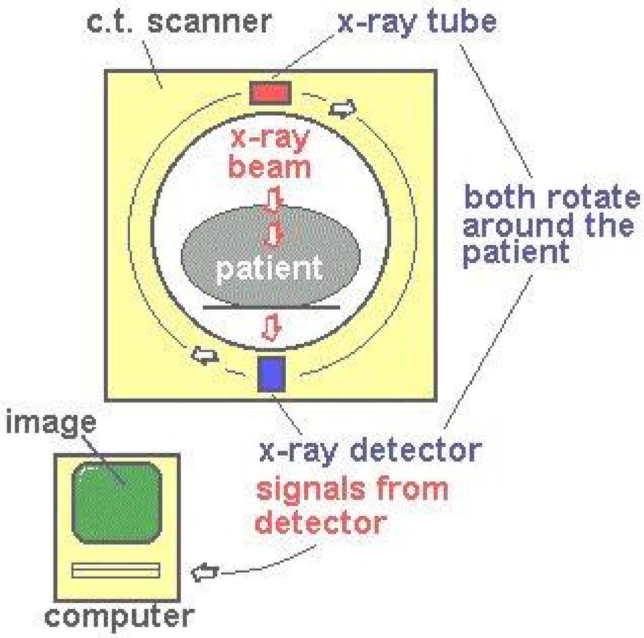
Computed Tomography (CAT Scan)

- Tomography is the technique of reconstructing an image from its projections



Abel (1826)

Radon (1917)



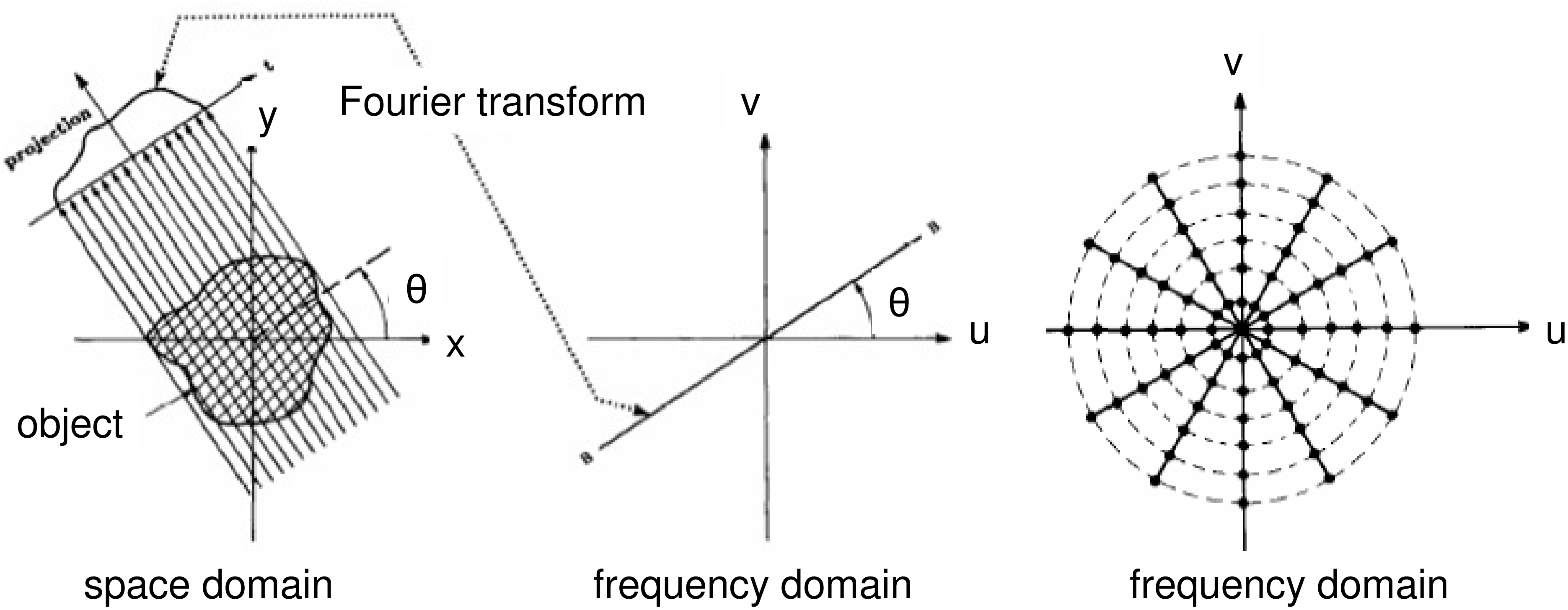
http://www.sv.vt.edu/

http://universe-review.ca

Tomography Algorithm

Fourier Slice Theorem

Fourier transform of a parallel projection is equal to a slice of the two-dimensional Fourier transform of the original object.

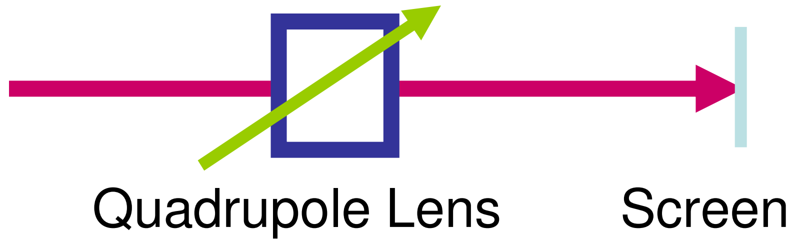


Kak and Slaney, Principles of Computerized Tomographic Imaging (1988)

Tomography Advantages-Disadvantages

- Pros
  - No a priori assumption about the distribution
  - Compact/ no need additional hardware
- Cons
  - In rings only applicable to first turn
  - Sensitive to screen linearity and camera quality

Quadrupole-Scan Tomography



- Quadrupoles rotate the phase space distribution.
- Single particle: $\boxed{x'' = -\kappa x + F_{SC}}$ $\qquad \kappa = \dfrac{qB}{\gamma m a v}$
- No SC: $x'' = -\kappa x$

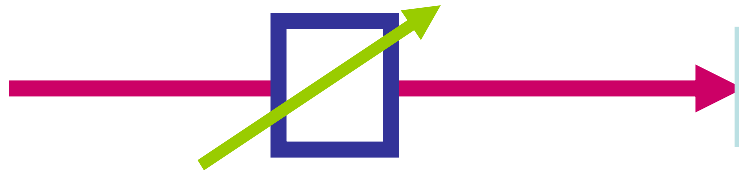
Is this equation familiar?

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos\sqrt{\kappa_x}\, z & \dfrac{1}{\sqrt{\kappa_x}}\sin\sqrt{\kappa_x}\, z \\ -\sqrt{\kappa_x}\sin\sqrt{\kappa_x}\, z & \cos\sqrt{\kappa_x}\, z \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

- With SC: Very complicated!

Solenoidal Tomography



$$\kappa = \left(\frac{qB}{2mc\beta\gamma}\right)^2$$

- Particle equation $\boxed{r'' = -\kappa r + \dfrac{p_\theta^2}{m^2 c^2 \gamma^2 \beta^2 r^3} + F_{SC}}$
- Where $p_\theta = \gamma m r^2 \dot{\theta} + q A_\theta r$
- If $p_\theta = 0, \quad F_{SC} = 0$ $\boxed{r'' = -\kappa r}$
- Case is similar to quadrupoles
- With SC: Very complicated!

Stratakis et al., Physics of Plasmas (Letter)14, 120703 (2007)

Beam Tomography with space charge

- Single particle equation: $\boxed{x'' = -\kappa x + F_{SC}}$

- Minimize the assumptions about the beam distribution

- Approximate space charge force as linear

- Validate through simulation (to be checked later)

Beam Tomography with space charge

- Single particle equation:

$$\boxed{x'' = -\kappa x + F_{SC}}$$

$$X = 2\sqrt{< x^2 >}$$

- Assume linear forces: $x'' = -(\kappa_{x,0} - \frac{2K}{X(X+Y)})x$

$$Y = 2\sqrt{< y^2 >}$$

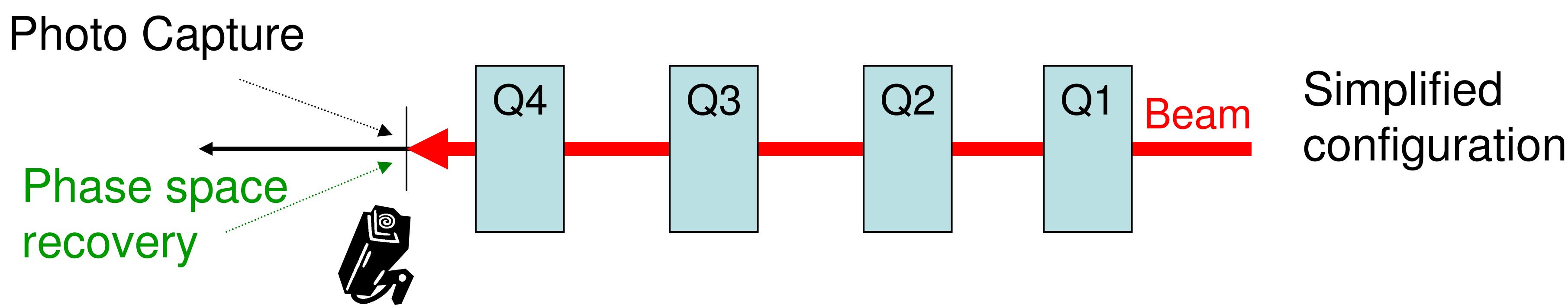
$$K = \frac{qI}{2\pi\varepsilon_0 m v^3}$$

- Find X, Y by solving envelope equations:

$$X'' + \kappa_x X - \frac{2K}{X+Y} - \frac{\varepsilon_x^{\ 2}}{X^3} = 0 \qquad Y'' + \kappa_y Y - \frac{2K}{X+Y} - \frac{\varepsilon_y^{\ 2}}{Y^3} = 0$$

Stratakis et al. Physical Review ST - AB 9, 112801 (2006)

Tomography Simulation/ Validation



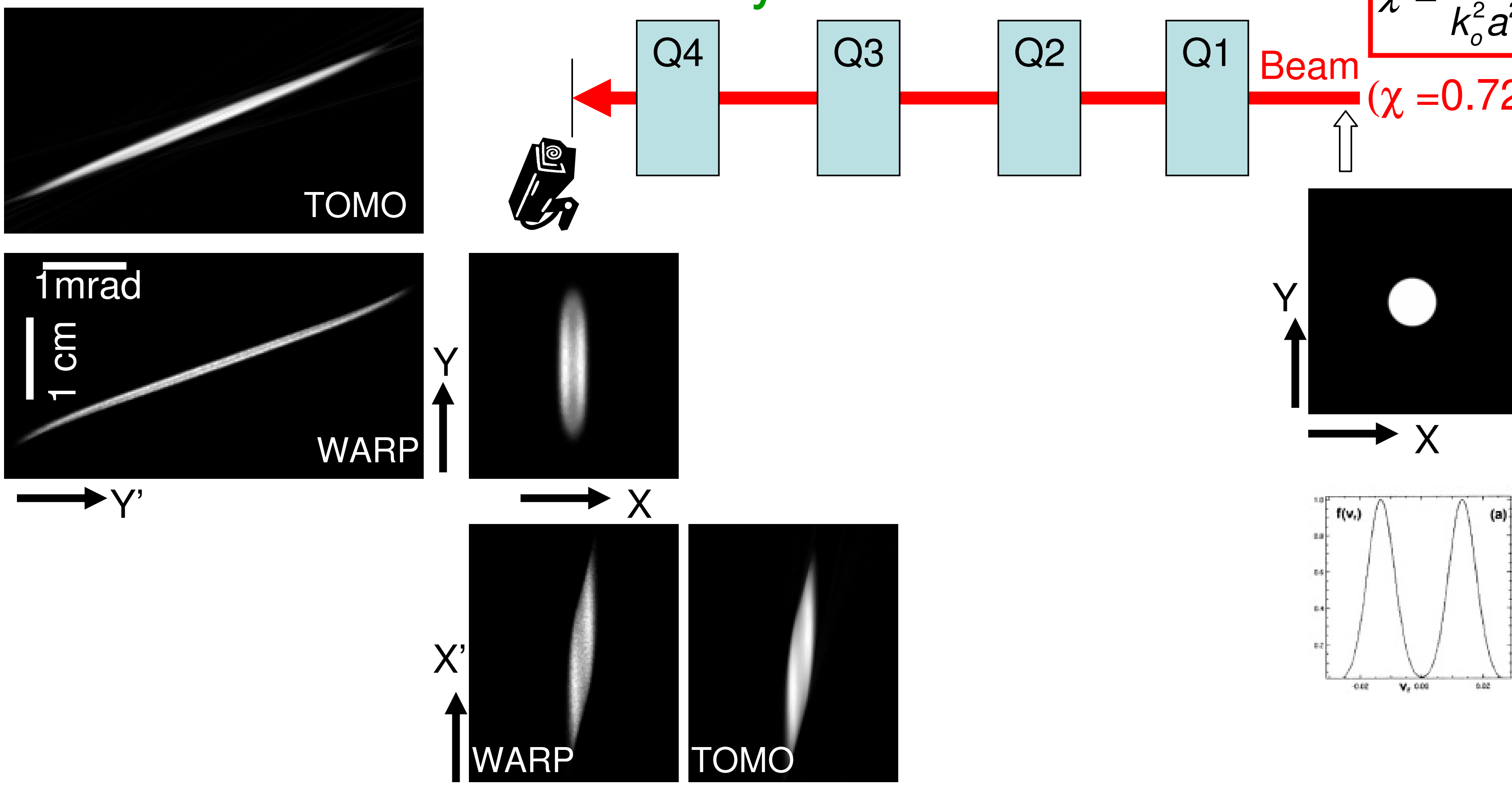
- Reconstructed phase space by Tomography will be compared to that generated directly by WARP

Tomography Simulation/ Validation

- Reconstructed phase space by Tomography will be compared to that generated directly by WARP.

Hollow velocity distribution

$$\chi \equiv \frac{K}{k_o^2 a^2}$$



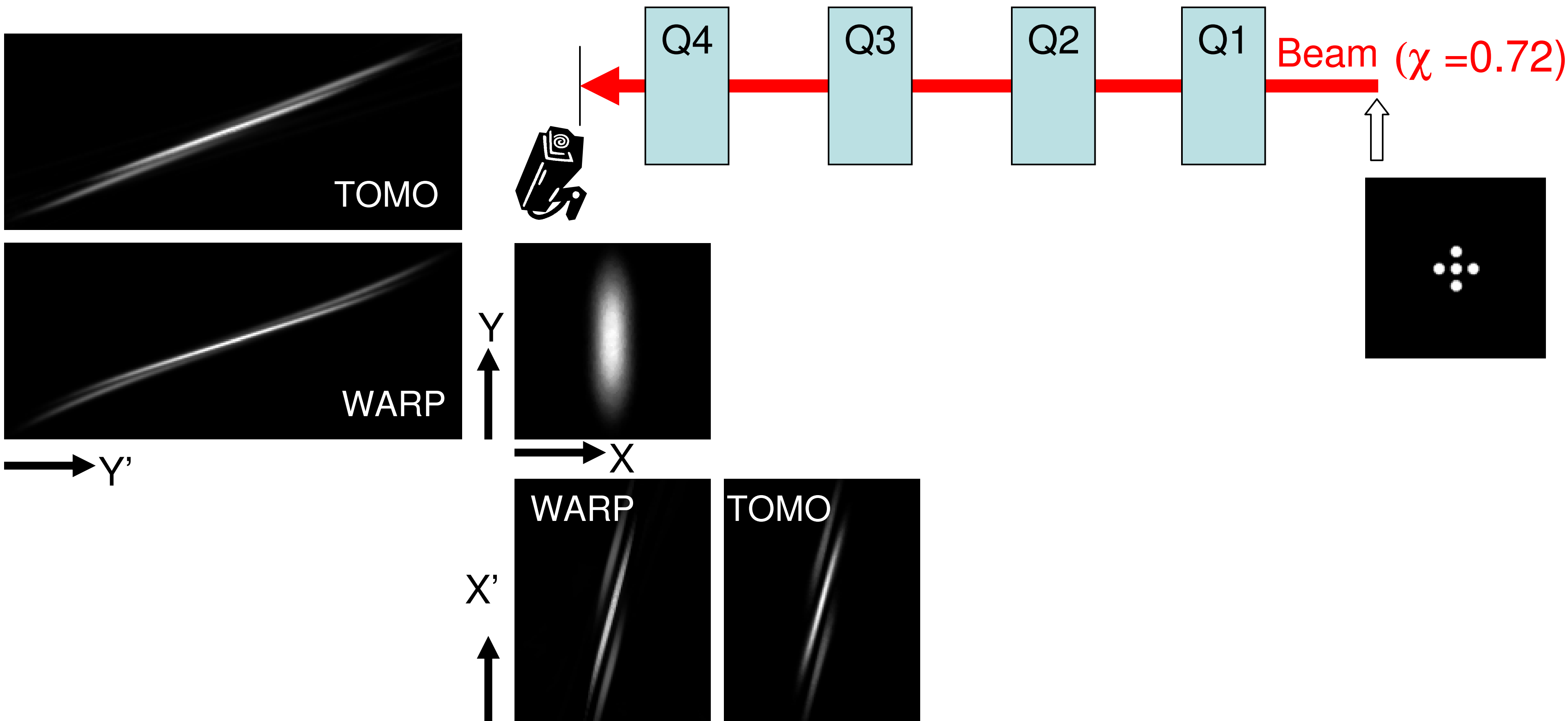
Stratakis et al. Physical Review ST - AB 9, 112801 (2006)

Tomography Simulation/ Validation

- Reconstructed phase space by Tomography is compared to that generated directly by WARP.

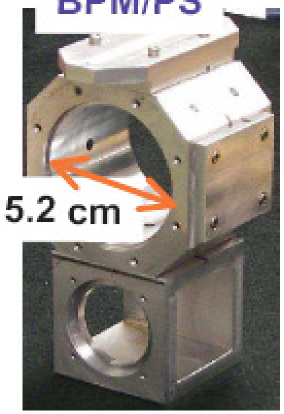
$$\chi \equiv \frac{K}{k_o^2 a^2}$$

Non-uniform spatial distribution

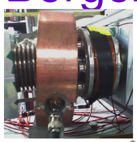


Stratakis et al. Physical Review ST - AB 9, 112801 (2006)

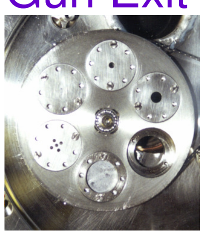
University of Maryland Electron Ring

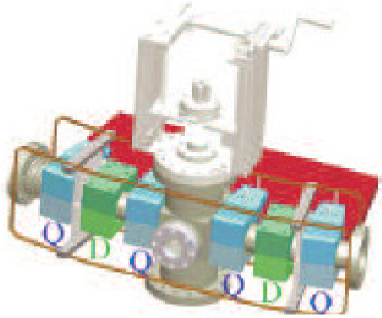


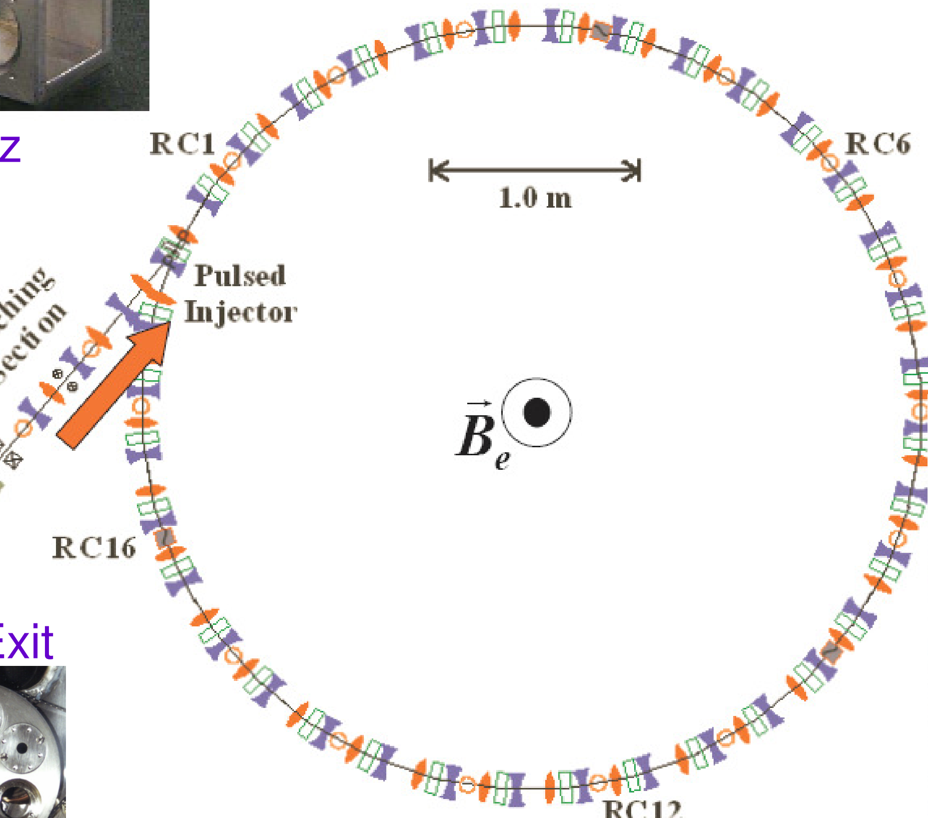
Bergoz



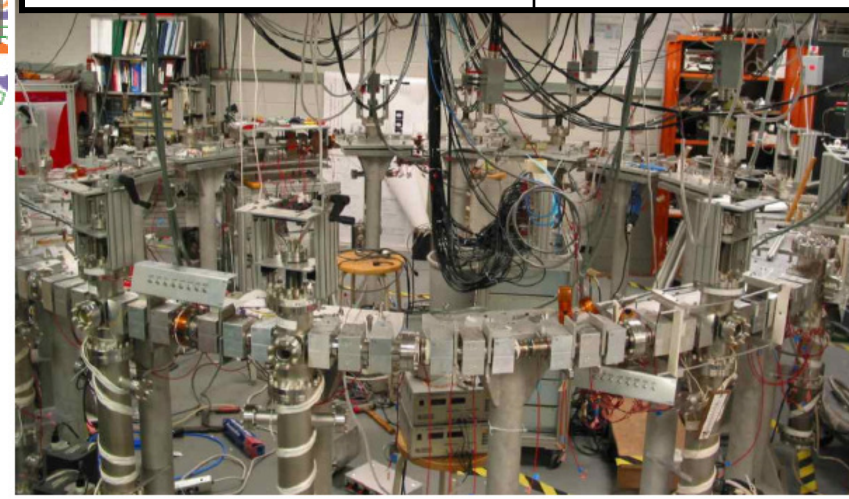
Gun Exit



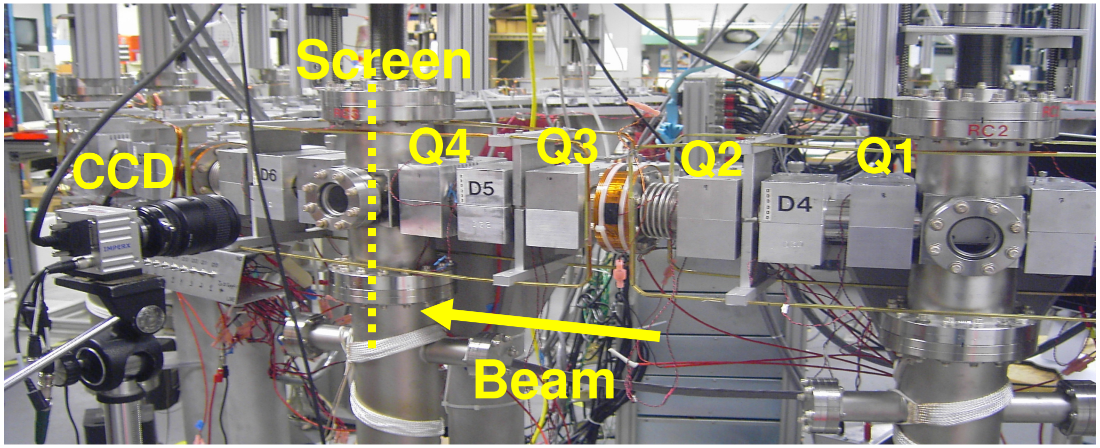




Energy	10-50 keV
rms Emittance, nor	0.2-3 µm
Current range	0.6-100 mA
Perveance	<0.0015
Circulation time	200 ns
Pulse length	100 ns
Zero-Current Tune	7.6
Depressed Tune	1.5 – 6.5



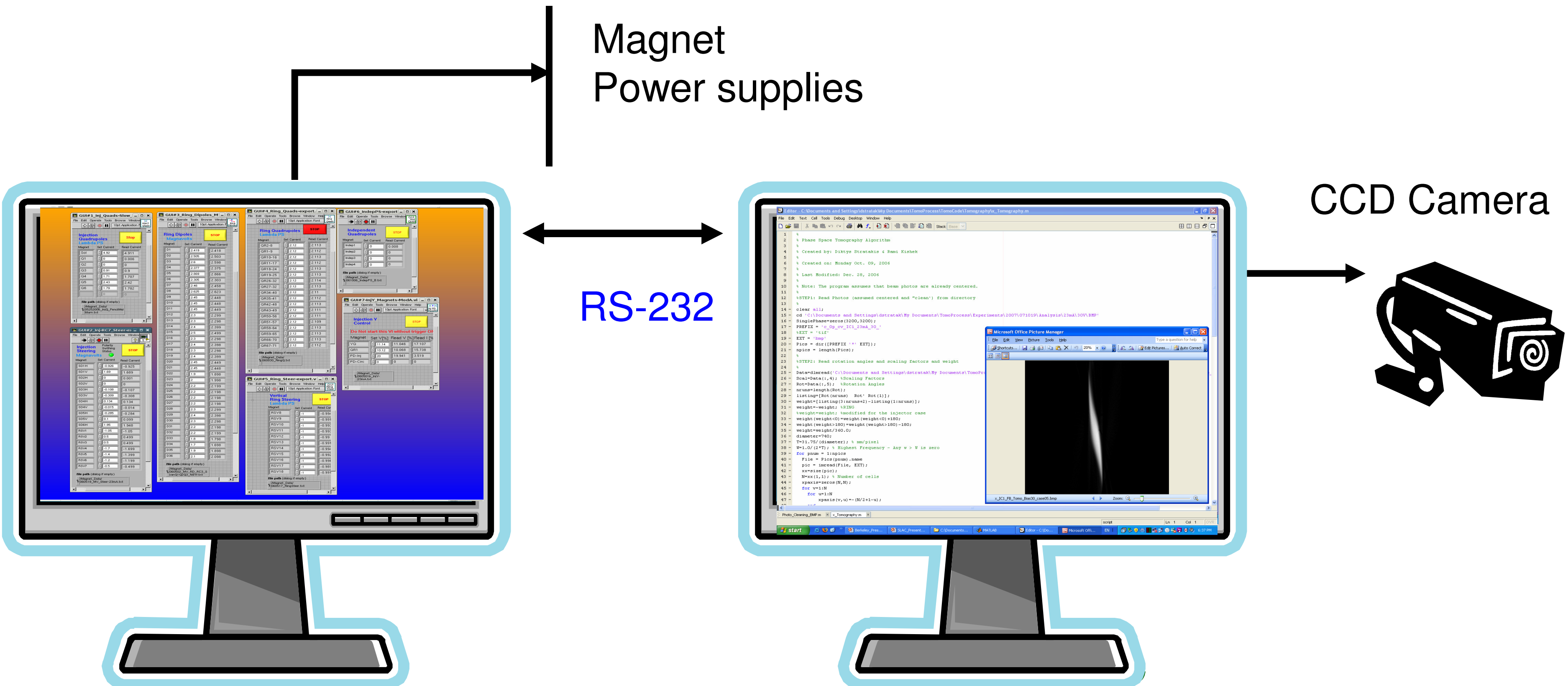
Tomography Experimental Configuration



- Screens
  - Gd_2O_2S:Tb (P43), 1.5 ms decay time
  - ZnO:Ga (E36), 2.4 ns decay time
- Cameras
  - IMPERX-1M48 (integrated)
  - PIMAX2 ICCD (gated)
- Lens
  - 60mm Micro Nikkor F/2.8 AF

Stratakis et al. PAC 2007

Computer Control System



Magnet Control Computer

Labview

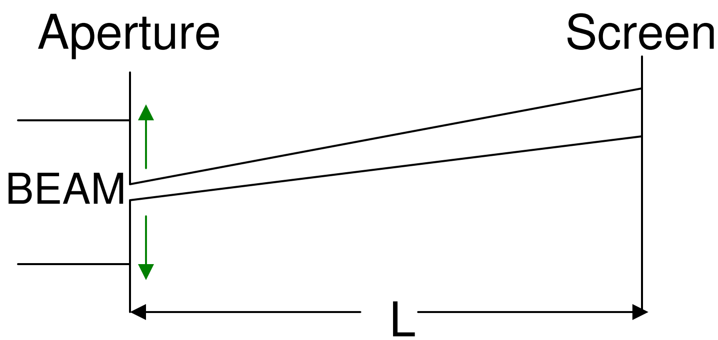
Tomography Computer

XCAP Imaging

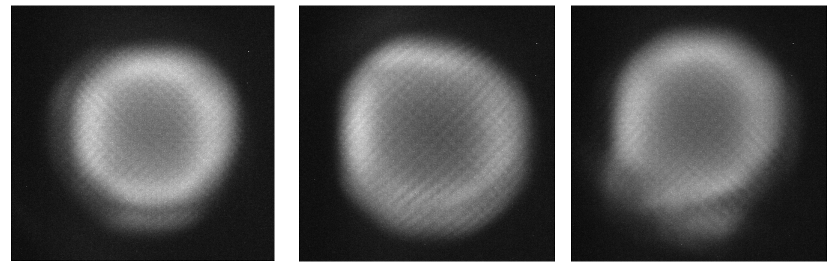
MATLAB

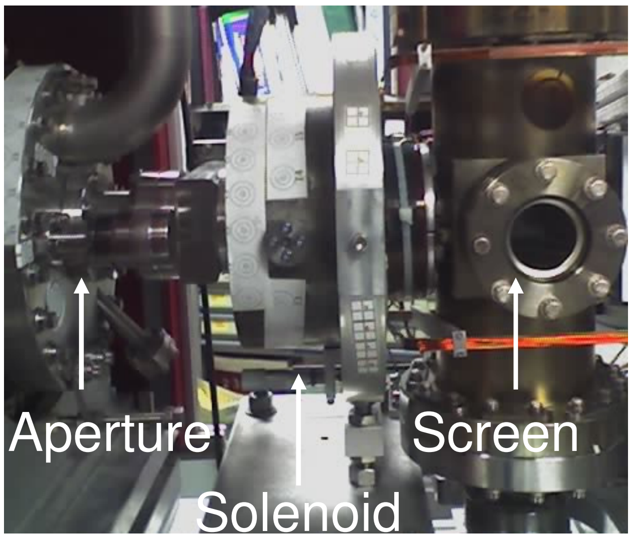
Stratakis et al. PAC 2007

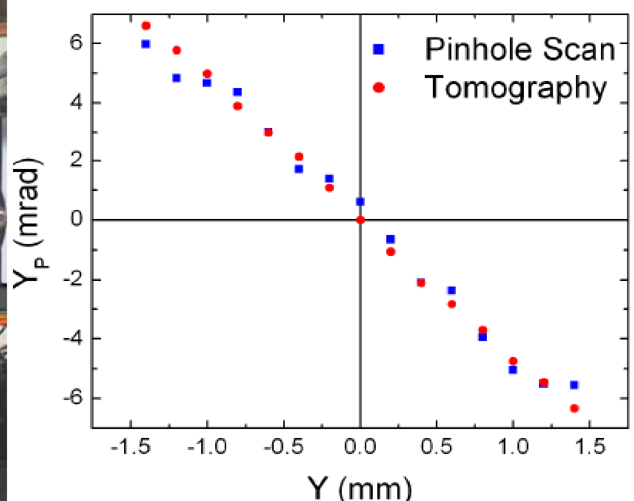
Experimental Validation of Tomography

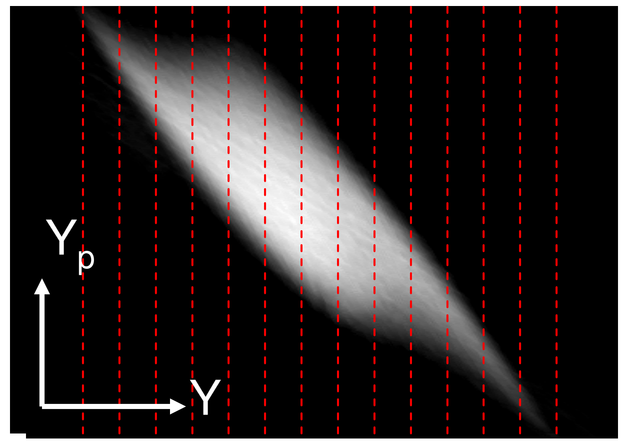


Pinhole Scan Screen Photos



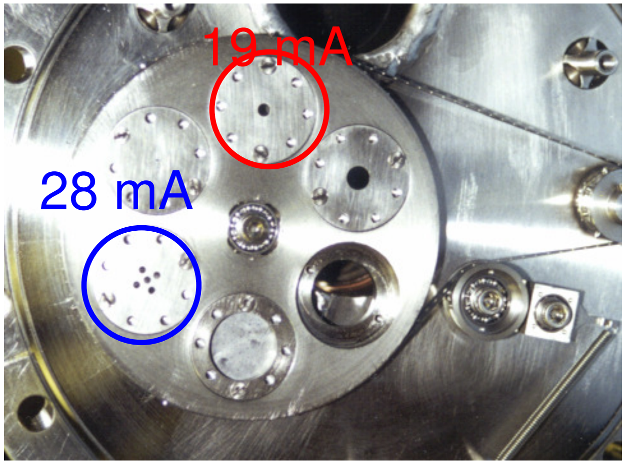






D. Stratakis, I. Haber, and S. Bernal, unpublished data

Three Experiments with Intense Beams

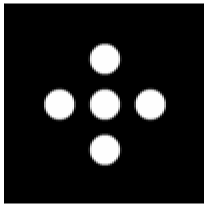


- Experiment 1:

  "Uniform" beam evolution (19mA, χ=0.85).

- Experiment 2:

  Nonuniform beam evolution (28mA, χ=0.9).



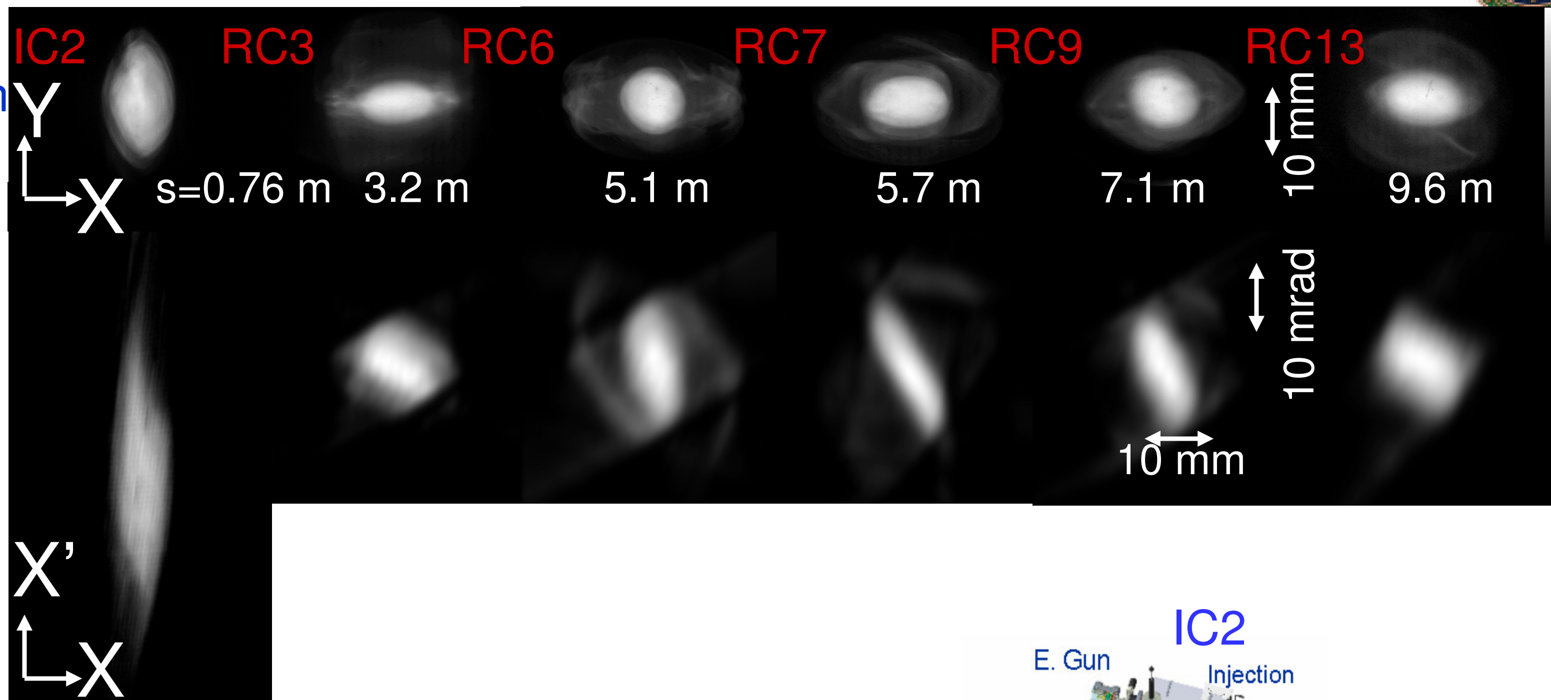
- Experiment 3:

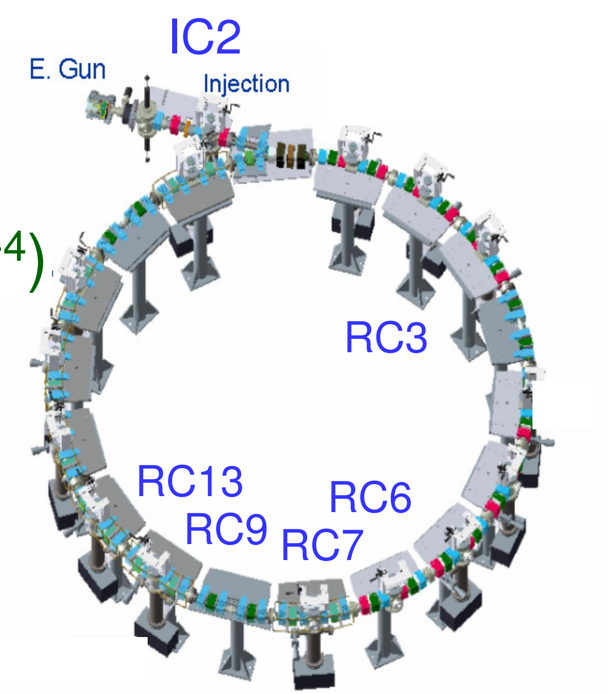
  Solenoidal Tomography/ Time Resolved Tomography

Single Beamlet Experiment

Configuration Space

Tomography Phase Space





Beam Parameters

e^- *beam* (E=10 keV, I=19 mA, K=3 10^{-4})

$a = 0.5$ cm

$\lambda_p = 1.14$ m

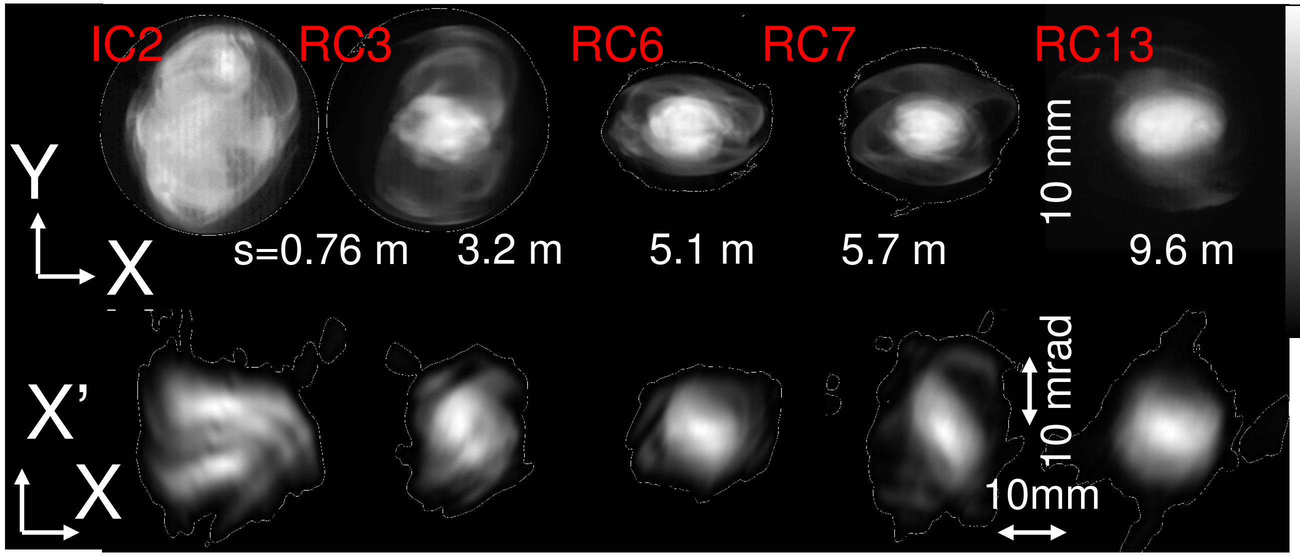
$\lambda_{\beta o} = 1.51$ m

$\lambda_\beta = 4.84$ m

Multibeamlet Experiment

Configuration Space

Tomography Phase Space



Beam Parameters

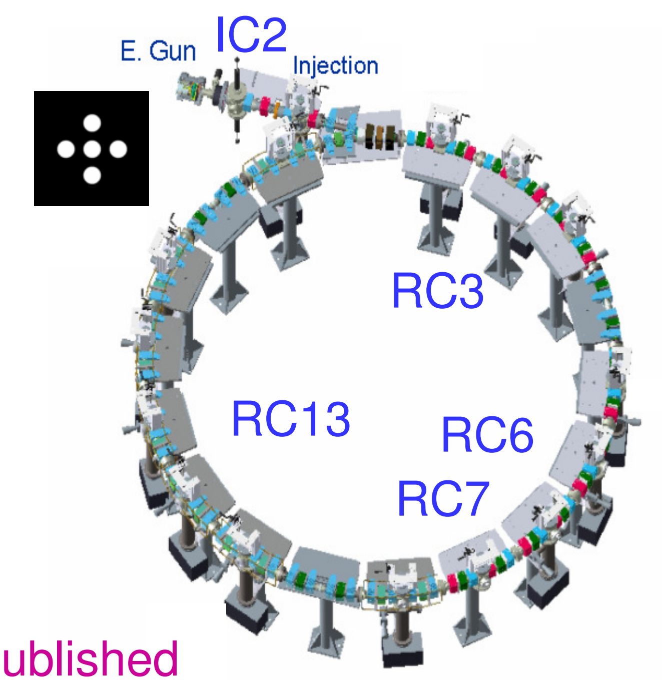
e^- beam (E=10 keV, I=28 mA, K=4 10^{-4})

$a = 0.6$ cm

$\lambda_p = 1.3$ m

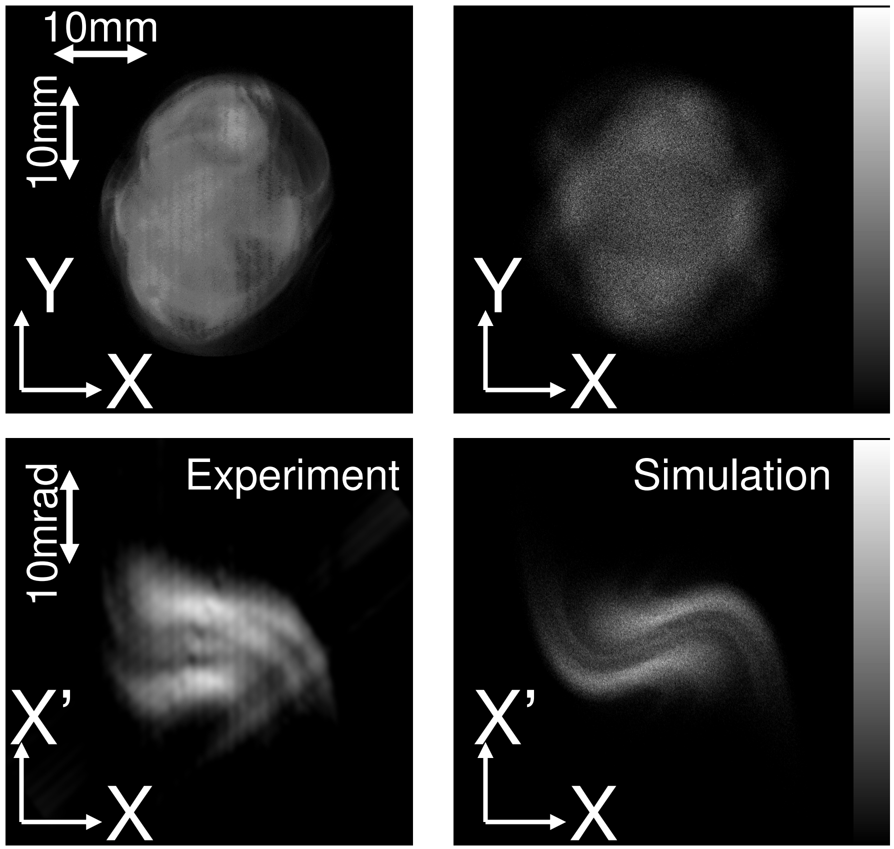
$\lambda_{\beta o} = 1.51$ m

$\lambda_\beta = 2.75$ m



Stratakis, Haber, Kishek, O'Shea, and Reiser, to be published

Multibeamlet Experiment Simulation



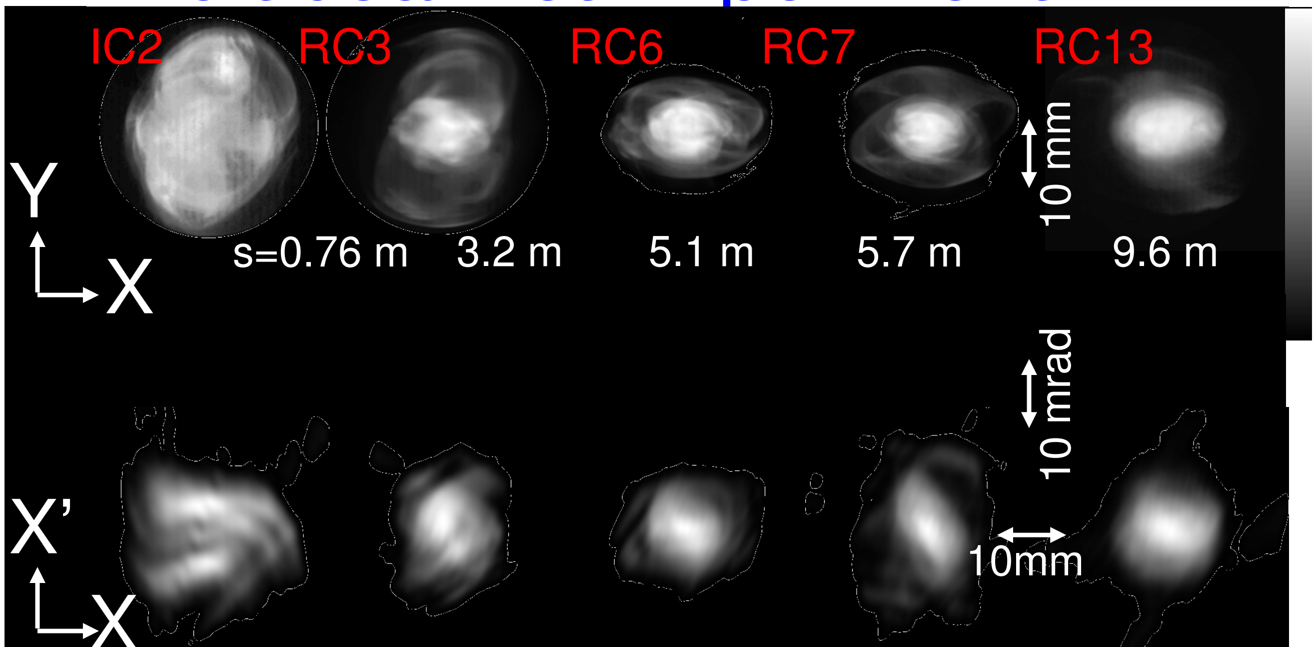
- Beamlets are well separated in phase space

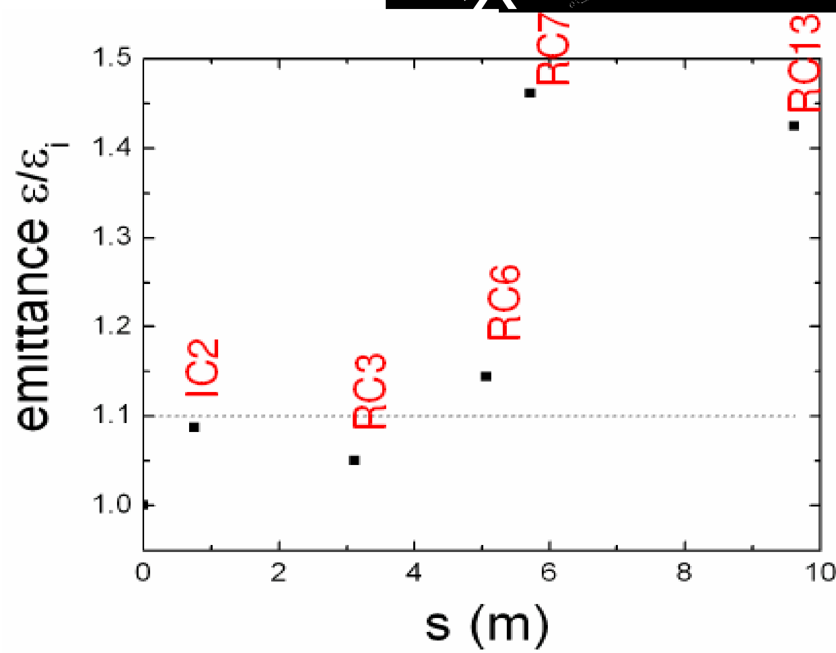
Stratakis, Haber, Kishek, O'Shea, Reiser, to be published

Multibeamlet Experiment

Configuration Space

Tomography Phase Space





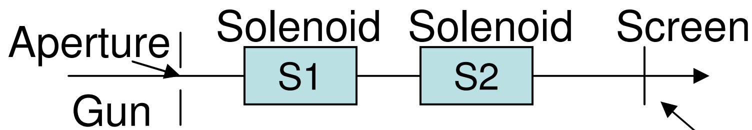
- Free energy conversion:

M. Reiser, PRL (1988)

$$\varepsilon_f / \varepsilon_i = 1.1$$

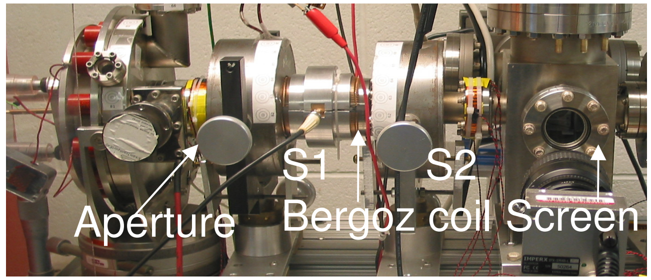
Stratakis, Haber, Kishek, O'Shea, and Reiser, to be published

Tomography with Solenoids



Reconstruction

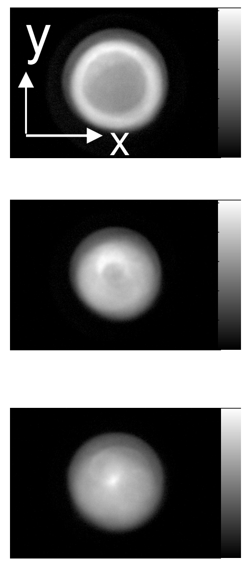
E=4keV
I=12mA



S1: 57G, S2: 60G

S1: 71G, S2: 60G

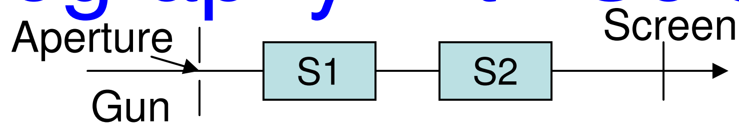
S1: 74G, S2: 60G

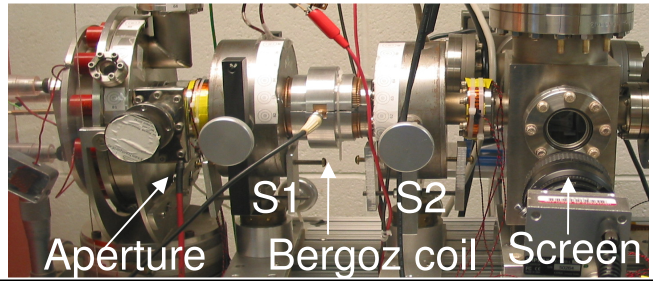


- Experiment reveals the presence of rings of particles

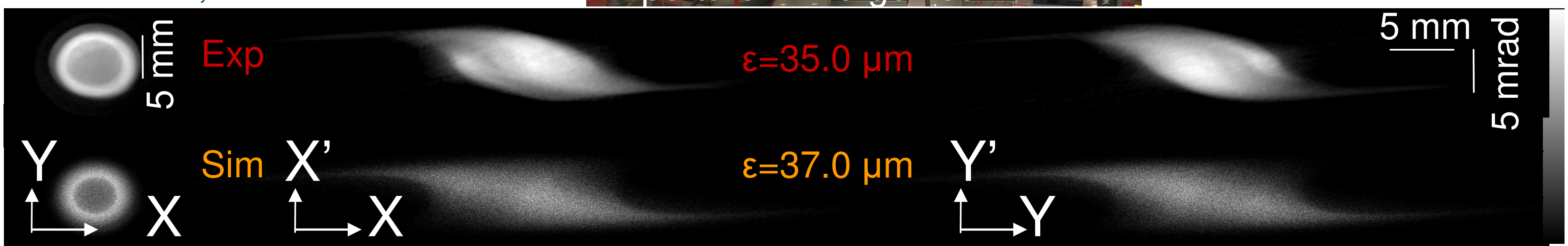
Stratakis et al., Physics of Plasmas (Letters)14, 120703 (2007)

Tomography with Solenoids

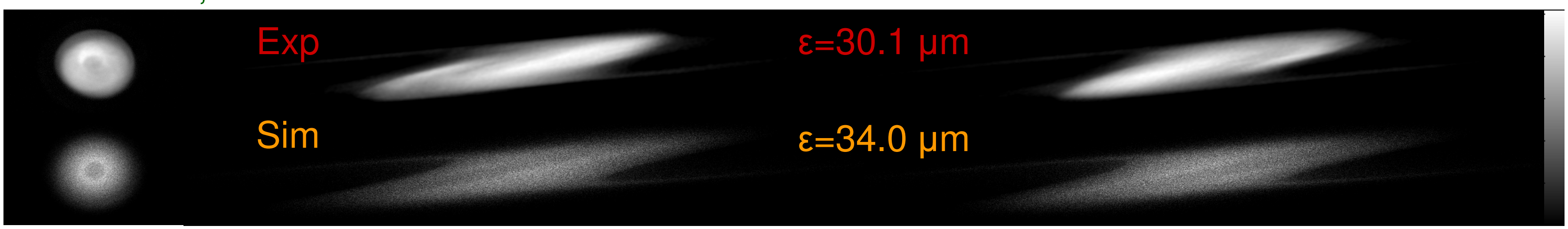




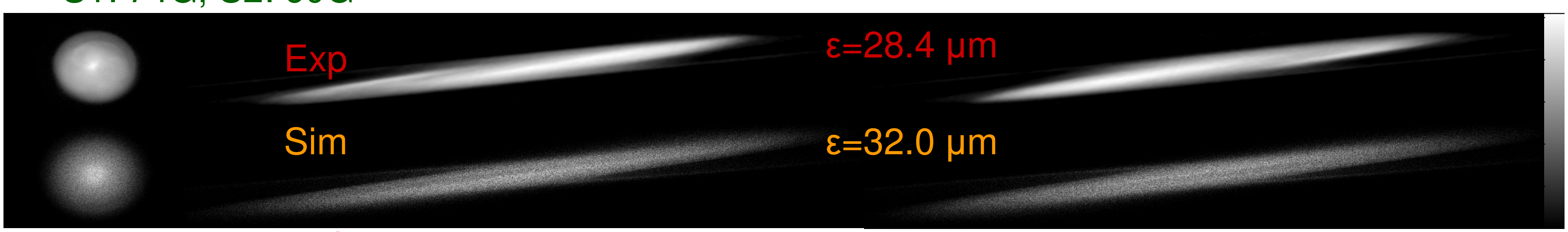
S1: 57G, S2: 60G



S1: 71G, S2: 60G

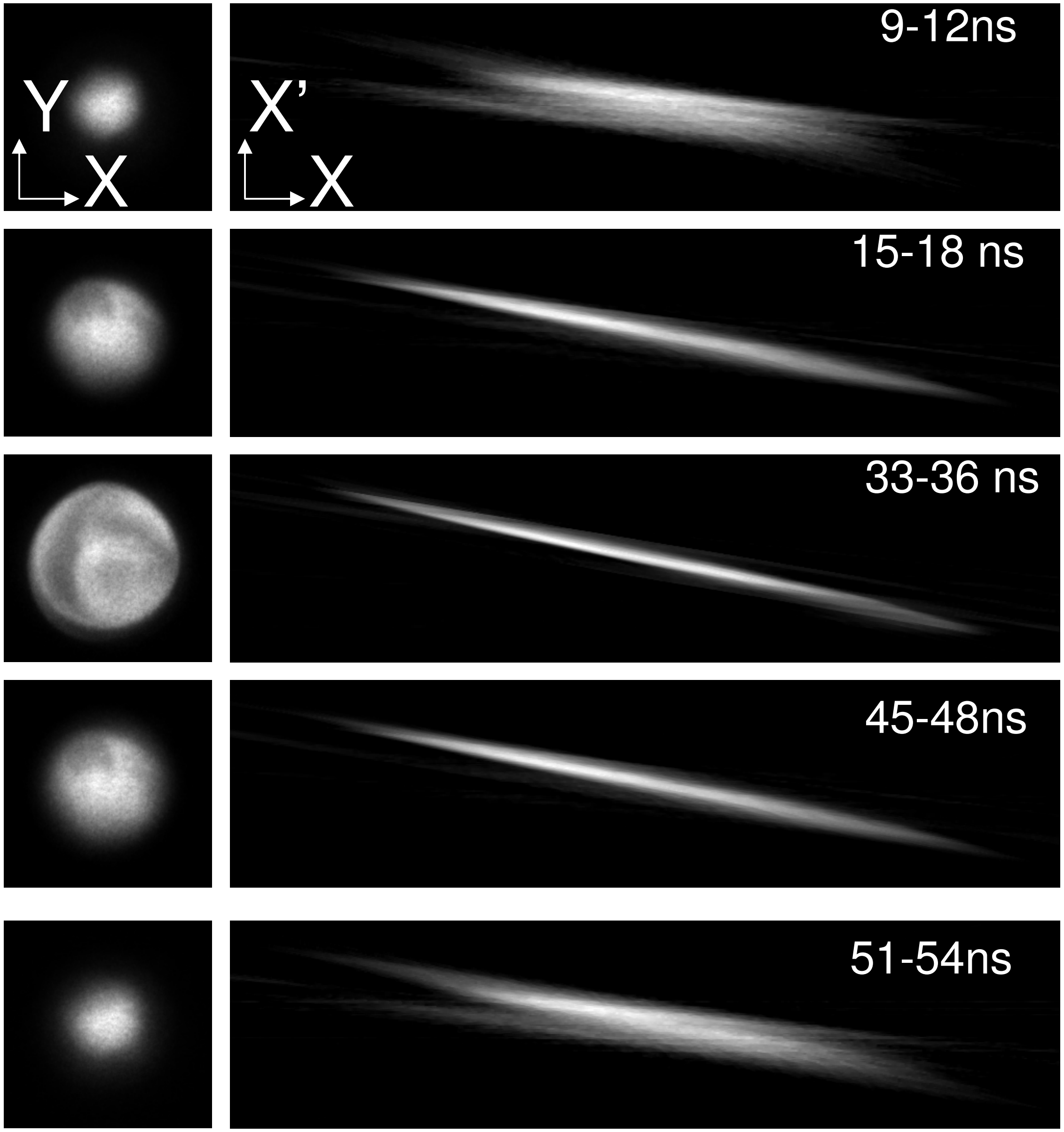


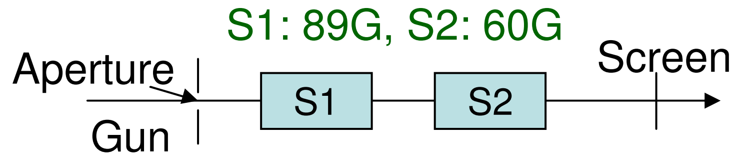
S1: 74G, S2: 60G

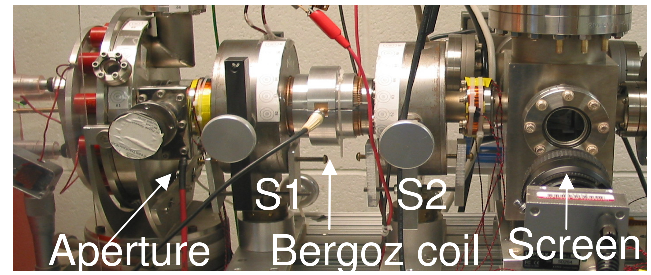


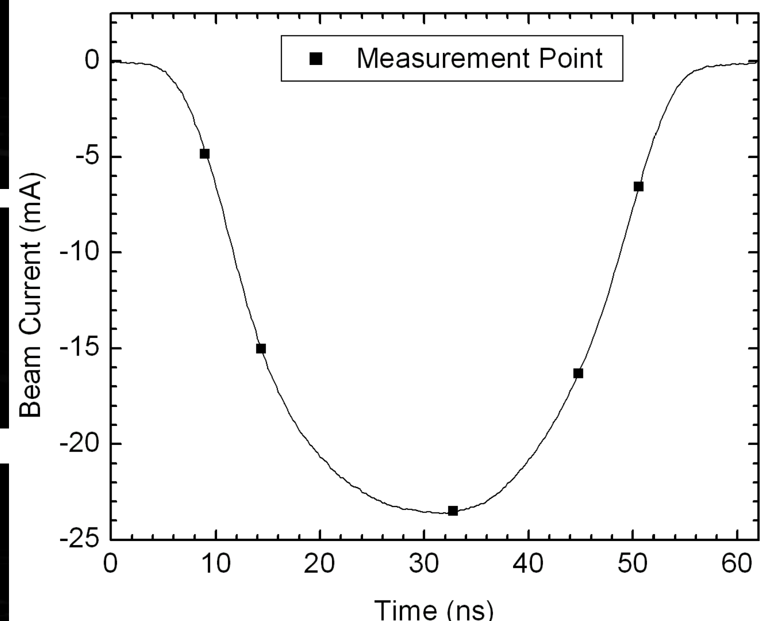
Stratakis et al., Physics of Plasmas (Letters)14, 120703 (2007)

Time Resolved Tomography (in progress)









D. Stratakis, K. Tian, J. Thangaraj, and R.B. Fiorito, to be published

Conclusions

- Extended Tomography to beams with Space Charge
- Simulation validated accuracy of technique
- Experimental measurements reveal evolution of beam halo and multi-beamlet merger
- Employed solenoids for tomography

PHYSICS OF PLASMAS **14**, 120703 (2007)

Tomographic phase-space mapping of intense particle beams using solenoids

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Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland 20742, USA

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **9**, 112801 (2006)

Tomography as a diagnostic tool for phase space mapping of intense particle beams

D. Stratakis, R. A. Kishek, H. Li,* S. Bernal, M. Walter, B. Quinn, M. Reiser, and P. G. O'Shea
Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland 20742, USA

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Not shown (but thanks, too):

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Dr. S. Lund (LBL)
Dr. V. Yakimenko (BNL)
Dr. H. Li (Microsoft)

<u>umer group</u>

- Dr. D. Sutter
- Dr. D. Feldman
- K. Tian
- B. Beaudoin
- M. Holloway
- C. Wu